UNMANNED GROUND VEHICLE NON-LINE-OF-SIGHT OPERATIONS USING RELAYING RADIOS

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ABSTRACT
Tactical mobile robots used in military and law enforcement operations normally require a robust, long range, and non-line-of-sight communications link to the remote control station. High frequency digital communications, which overcome problems encountered by tethered links and analog radios, are subject to line-of-sight (LOS) limitations. This is often impossible to maintain in urban environments. The proposed solution is to develop a system that will allow the mobile robot to carry multiple relay radios that are automatically deployed when and where needed in order to maintain this communications link. This process is completely transparent to the operator and is entirely handled by the ad-hoc network formed by the relay radios. In this paper, we present a radio relay deployment system that is plug-and-playable, and can be attached to many unmanned vehicles requiring long-range and non-LOS operational capability.

KEY WORDS
Telerobotics, communications, relays, ad hoc networking

1. Introduction

The communications link between a tactical mobile robot and its control station is often a limiting factor for the overall system. Mobile robots used by the military and law enforcement agencies require a robust communications link for successful mission executions. Such mobile robots are increasingly used in life-threatening situations and hazardous environments [1], rendering a solid communications link to be of vital importance.

In such situations using a tethered system is problematic. They can be cumbersome, have limited range, and can snag or break as the robot maneuvers around obstacles or inadvertently runs over the cable. Analog radios have limited bandwidth and suffer greatly from multi-path fading. Wireless broadband digital communications, on the other hand, have proven to be much more robust and versatile. However, due to their high operating frequency, maintaining a line of sight (LOS) with the control station is a requirement that is impossible to obtain in certain environments. This problem can be somewhat alleviated by proper antenna placement and signal amplification, but these methods are limited by real estate and spectrum-use regulations, respectively. As a result, users have often expressed desire for a radio relay system. We propose an automatic radio relaying system that is completely transparent to the user and the operation of the robot.

2. Background

The current project is based on our previous effort completed for the Defense Advanced Research Projects Agency (DARPA) under the Autonomous Mobile Communication Relays (AMCR) project. The goal of this prior work was to demonstrate the use of mobile relay nodes that follow a lead robot in a convoying fashion as it traverses an unknown environment. The mobile relay nodes stop automatically when needed in order to form an ad hoc network and maintain the communications link back to the control station. The relay robots, equipped with Laser Radar (LADAR) and sonar sensors, are capable of obstacle avoidance and path planning as they travel in the convoy. The lead robot, also equipped with a LADAR, is also capable of mapping the environment.

2.1 Convoy

The convoy formation comprises a lead robot, followed by several relay robots, as shown in Figure 1. Each relay robot is programmed to follow the one immediately in front of it. With the exception of the rear robot in the convoy, all others are fitted with a retroreflective bar code [2] with a unique binary identification code. Based on this bar code, each relay robot, using its LADAR, obtains range, bearing, and orientation [3] information of the robot in front. This information is used for steering and velocity calculations in order to maintain the convoy formation, while simultaneously avoiding obstacles using additional sonar and LADAR data. In order to provide transparent relaying capabilities, the rear-most robot in the convoy will automatically stop as required to become a stationary relay node, while the rest of the convoy (and the lead robot) continues its mission. The process continues until all relay robots have been used.

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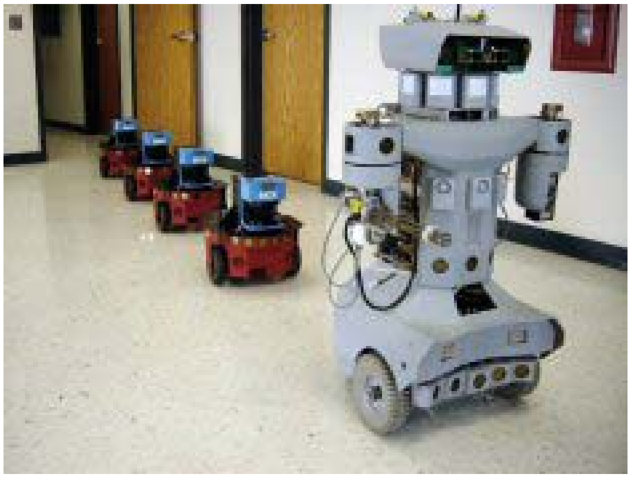

Figure 1. Convoy formation shown with SSC-SD's Robart III as the lead robot, followed by ActiveMedia Pioneer 2DX relay robots.

2.2 Network

The networking software [4] was developed by BBN Technologies under a separate DARPA project. The ad hoc network (based on IEEE's 802.11b protocol) formed by the radios uses a proactive link-state protocol. Each node in the network has complete information about the characteristics of all links. It can execute a routing algorithm of its choice and determine the paths most suitable for the chosen criteria. Each node uses broadcast messages, sent at intervals determined by the network criteria and the environment, to determine the characteristics of the link and set up the routing table. This table is recomputed whenever certain network events occur, such as when the link quality between two nodes drops below a predetermined level chosen for the scenario, or when a new node enters the network. The routing table can then be updated before a link is broken, automatically maintaining the network in a proactive fashion for optimal information transmission and lag. There is no delay incurred due to route reselection caused by broken links.

Each relay robot in the convoy monitors its received radio signal strength to the node immediately behind it. As the signal-strength drops to a threshold determined by a predictive filter, the relay robot stops to prevent further signal degradation that could lead to link breakage. This process guarantees that there would always be at least one path between the lead robot and the base station. (This may not necessarily be the path currently used, as there could be shortcuts, for example, directly between the lead robot and the base station.)

BBN Technologies has also developed energy conservation methodologies [4] that can be incorporated into the radios. Geared towards unmanned systems and sensors that require communication over an ad hoc network over extended periods of time, these energy conservation schemes greatly enhance the operating period, further minimizing direct user interaction with the system. Due to hardware memory limitations, these methods are not implemented into the relay radios at this time.

2.3 Compact Ad Hoc Networking Radio (CANR)

The networking software developed by BBN Technologies has been implemented in a relaying radio slightly larger than a pack of playing cards (the CANR). The radio comprises Bright Star Engineering's nanoEngine (a small Single-Board Computer using Intel's StrongARM processor), a commercial PC Card 802.11b radio, and the Radio Interconnect Board (RIB) developed by SSC-San Diego. The nanoEngine and the PC Card radio plug into the RIB, which provides regulated power to both and access to serial and Ethernet ports.

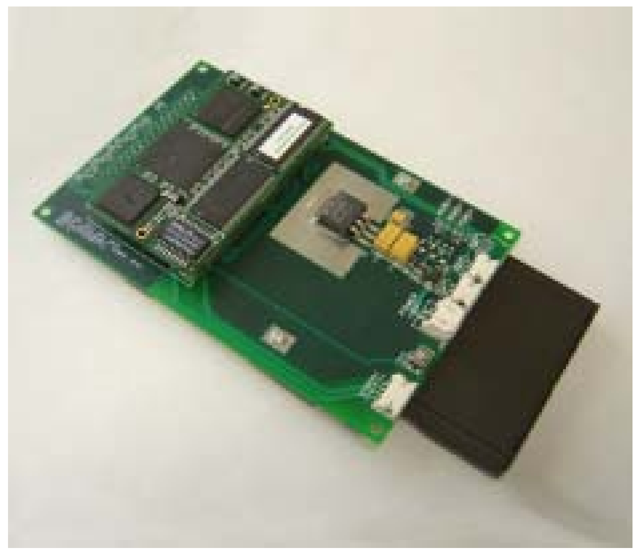

Figure 2. Top side of the CANR showing the nanoEngine, with the PC Card (bottom side) plugged into the RIB.

The success of this Compact Ad-hoc Networking Radio design led to the development of over one hundred units for use in other DARPA robotics projects at the University of Pennsylvania, Georgia Institute of Technology, University of Southern California, and BBN Technologies, as well as other in-house robotics projects. A second generation RIB was subsequently developed that offered greater functionality, such as the addition of a second PC Card slot, a host USB controller, and improved power management for greater efficiency. The second PC Card slot can be used for a second 802.11b radio to provide higher speed relaying through the simultaneous use of two different radio channels, or a GPS receiver that can be used to track mobile units outdoors. The USB port allows the use of inexpensive USB cameras to provide audio and video surveillance information from each relay node in the network, allowing the nodes to also act as rear guards, securing areas already cleared by the lead robot.

2.4 Convoying Demonstrations

Two convoying experiments were performed to demonstrate the automatic relaying capability [5]. One took place in a mixed indoor/outdoor environment, and the second in an underground bunker.

A Segway RMP [6] was configured as the lead robot for these demonstrations. Three ActiveMedia Pioneer 2-DX robots were used as the mobile relay nodes. Each Pioneer was equipped with 16 Polaroid sonar sensors used for obstacle avoidance. Each robot was equipped with a SICK LMS 200 LADAR, which was used for obstacle avoidance, identification of the robots in front through retro-reflective bar code beacons, and beacon-based self-localization.

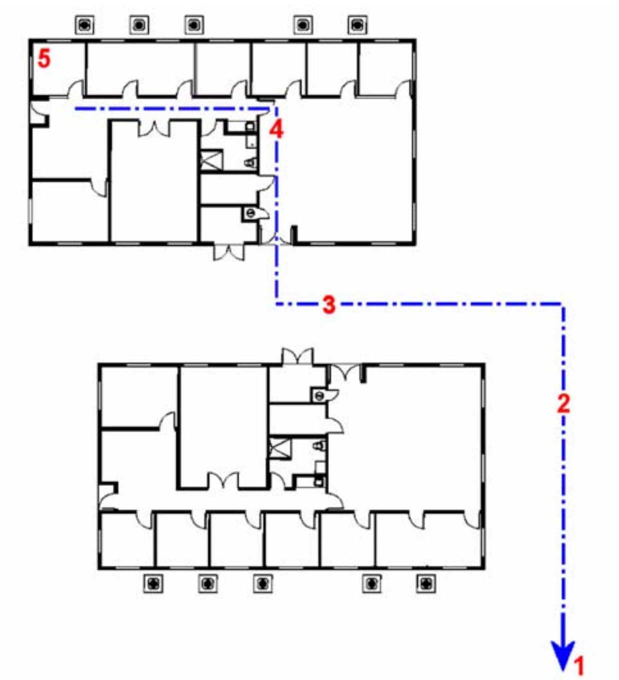

Figure 3. Final locations of the lead robot (1) and the relay robots (2, 3, and 4) along the travel path away from the control station (5), at the end of the mixed indoor/outdoor demonstration.

Figure 3 shows the path taken by the teleoperated lead robot along with the final locations of the relay robots. Node 1 is the lead robot and node 5 is the control station. The control station included a CANR connected to a laptop computer that received audio and video information from the lead robot, which the operator used to maneuver it along the path shown. As LOS was lost between two adjacent radios the associated relay robot stopped to maintain the link. The final locations of the relay nodes correlated fairly accurately with predicted locations based on LOS simulations.

The second experiment took place in an underground bunker with thick concrete walls that resemble environments like those of tunnels and caves. As seen in Figure 4, the relay nodes stopped as LOS was lost.

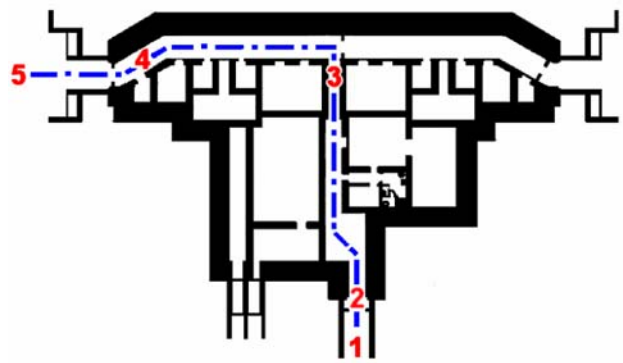

Figure 4. Final locations of robots shown along the path taken through an underground bunker.

The relaying system allowed the lead robot (1) to be teleoperated from one side of the bunker to the other, a feat that would not have been possible normally.

2.5 Transition

Using mobile relay nodes allows for possible automatic recall of the nodes upon mission completion, as well as repositioning of the nodes on-the-fly. However, it is not practical for tactical applications calling for compact, light weight systems that can be rapidly deployed. Using mobile relay nodes would require transporting not only the lead robot but the relay robots as well, which may add logistical challenges. Initial setup of the convoy may add unacceptable delays. It is possible for the relay robots to be of smaller size and lighter weight than the lead robot, however, this introduces new problems. The relay robots must be able to traverse the same terrain as the lead robot, which is not usually possible with smaller robots. Cost is another issue. A relay robot must carry sophisticated sensors, processor boards, batteries, and have an appropriate drive train, in order to follow in the convoy and simultaneously avoid obstacles. This amount of complexity and the introduced maintenance requirements greatly adds to the cost of the system.

In a more practical system the relay robots are eliminated, instead the lead robot carries the relay radios and drops them off as needed to maintain the link. This approach greatly simplifies the system, significantly reducing weight, cost, maintenance issues, and provides rapid deployment capabilities. The feasibility of using this method is being demonstrated under the Automatically Deployed Communication Relays (ADCR) project, funded by the Office of the Secretary of Defense (OSD) Joint Robotics Program (JRP).

3. ADCR System

The goal of the ADCR project is to develop a practical, stand-alone, plug-and-playable deployment system capable of carrying relay-radios that are automatically released when needed in order to maintain the communications link back to the control station. This

system, requiring no external power, attaches to the payload area of an unmanned ground vehicle (UGV) and interfaces to the UGV through an Ethernet port.

The basic components include several relay radios that plug into a deployment mechanism. The packaged relay radios, known as Relay Bricks, are self-contained ruggedized CANRs that are carried aboard a module called the Deployer, which is carried by the UGV. The Deployer releases the Relay Bricks as needed to maintain the link. Once dropped off, the Relay Brick will right itself and raise its antenna to establish proper radio connectivity. At the end of the mission the Relay Bricks may be collected and easily stowed back in the Deployer without the need of any tools.

The deployment system is currently limited to UGVs that are capable of communicating over the Ethernet standard. This limitation is based on the network formed by the Relay Bricks, which use the IEEE 802.11b protocol. The advantage, however, is that this common and versatile protocol allows the system to be plug-and-playable, with minimal modifications to the UGV hardware and network setup. Most of the modern UGVs already use this Ethernet standard.

3.1 System Overview

Due to size constraints of the Relay Bricks and the Deployer, the current design allows the Deployer to carry six Relay Bricks. The Deployer also contains a dedicated, onboard CANR, which is connected to the UGV through the Ethernet port. An additional Relay Brick provides network connection to the Operator Control Unit (OCU) at the control station.

A basic network of two nodes is formed when the control station and the Deployer CANRs are communicating. Additional nodes enter the network as each Relay Brick is activated and released as needed. It takes approximately 40 seconds for a radio to fully boot. To eliminate this delay and prepare a Relay Brick for immediate release, one Relay Brick in the Deployer is always powered and ready. This allows the network to immediately take advantage of this node and reroute the communications path without any incurred delay, as discussed in Section 2.2. Immediately after the release of a Relay Brick, the next Relay Brick is powered and ready for release. This cycle continues until all units have been spent.

3.2 Relay Brick

The Relay Brick (Figure 6) is a self-contained, ruggedized CANR designed to work in outdoor environmental conditions. As such, it must adhere to several requirements: 1) be watertight, 2) withstand shock of impact after release, 3) self-righting to raise the antenna, and 4) consume low power for increased operational period.

The Relay Bricks are designed to absorb approximately 100 Gs of shock to withstand the impact of hitting the ground once released from the Deployer. This was necessary to insure that the PC Card and the nanoEngine stay securely connected to the RIB.

Once the Relay Brick has been released and resting on the ground, it must automatically right itself so that it can raise its antenna for proper signal relaying. To accomplish this, small bumps are added to its ends to prevent it from resting on them. Next, spring-loaded bay doors, which must open to release the antenna, are used as a self-righting and support mechanism to ensure that the brick always ends up on its bottom side. As the bay doors fly open, the antenna lift mechanism, also spring-loaded, extends to a pre-selected height.

The antenna height is of vital importance. Antennas placed close to the ground suffer from increased multi-path interference, surface-wave attenuations, and Fresnel Zone violations [7]. Therefore, the antenna height has been maximized as much as possible based on design constrains, such as, available real estate and the practicality of the antenna lift mechanism. The goal is to attempt to minimize such losses to obtain the greatest possible communications range. Computer simulations were conducted to provide approximate maximum attainable range as a function of antenna height, under best case scenarios. Simulations were performed over a flat ground, with the ground being made perfectly reflective in one case and made out of sandy soil with a dielectric constant of 2.55, in the other.

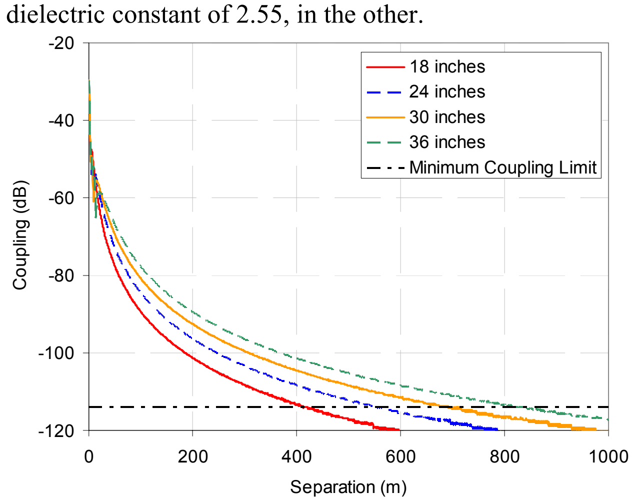

Figure 5. Coupling simulation results over a flat sandy soil ground.

Figure 5 shows the simulation results over the sandy soil ground. The minimum coupling between antennas, which provides the maximum range, is shown to be -114dBm. This value is derived by considering the signal gain and the minimum receiver sensitivity of the Cisco Aironet 350 Client Adaptor. Results verify that as the antenna height is increased, the maximum range increases. Based on design constraints and simulation results, the Relay Brick antenna is designed to stand 21 inches above the ground as measured from the ground to the dipole feed point.

The available antenna real estate in the Relay Brick allows only the use of half wavelength antennas that are small enough in size, which narrows the selection down to dipole antennas with a 2dBi gain. Several candidates were chosen and their patterns verified in an anechoic chamber. An antenna from 3COM [8] was chosen because it provided the cleanest antenna pattern.

Special attention has been paid to the operational time and power consumption of the Relay Brick. Various rechargeable battery chemistries were studied in order to select one that provides the greatest power in the smallest package, due to real estate constraints. Running on Li-ion batteries and using onboard high-efficiency DC-DC converters allow the Brick to function approximately 10 hours, well over the operating time of most battery powered UGVs. While off, the Brick electronics consumes extremely low levels of power, allowing it to last months without recharging. A small, user interface window provides shut-down, manual power activation, and available battery capacity readout features.

Figure 6. Relay Brick, shown as open and antenna mast extended.

3.3 Deployer

The Deployer is the module that attaches to a UGV and interfaces to it through the Ethernet port. The current design allows it to carry six Relay Bricks. Due to various shapes and sizes of candidate UGVs, a unique attachment bracket must be designed for each UGV.

The Deployer is also designed to operate outdoors and is in charge of the following: 1) automatically releasing the Relay Bricks when needed, 2) reporting status to the user at the control station.

The Relay Bricks are easily stowed in the Deployer by loading them in individual chambers (see Figure 7). Each chamber contains a spring loaded catapult, onto which the Relay Brick rests, and a push-pin that locks the Relay Brick inside the chamber. Servo motors linked to the push pins release the lock, launching the Relay Bricks out of the Deployer when needed. Once locked into place, the Relay Bricks can be manually released by pressing on a manual override button located close to the chamber opening.

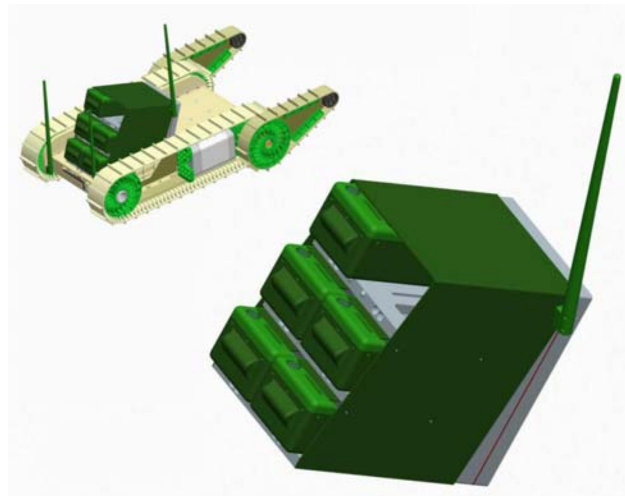

Figure 7. Deployer module shown with one empty chamber. Placement of the Deployer onboard the iRobot PackBot is also illustrated.

As discussed in Section 3.1 a Relay Bricks must be activated prior to launching. This is accomplished by the use of an electromagnet residing under each chamber and a magnetic reed switch located inside each Relay Brick. When the electromagnet is activated the reed switch closes and sends a signal to the standby circuitry, which in turn provides power to the system. Other methods of power activation were considered and rejected due to the requirements of additional hardware or the impracticality of using such methods in outdoor environmental conditions.

Whether or not a Relay Brick was successfully launched or not is detected by a detect switch inside each chamber. If a Relay Brick fails to launch the next Relay Brick in the Deployer is activated and launched.

Even though the relay deployment process is transparent to the operator, a remote manual relay-release override option will be provided. During mission execution the operator may realize that his current tactical position may need to change, therefore a Relay Brick may be prematurely released so that it can still provide connectivity from the new position of the control station.

The CANR aboard the Deployer is essentially the heart of the system. It monitors network events and

communicates them to the Deployer microcontroller using the Application Programming Interface (API). The communication takes place over an RS232 port. The microcontroller interprets these events and takes action. If, for example, the link is about to break, the CANR signals the microcontroller to release a Relay Brick. The microcontroller then unlatches the lock and the spring-loaded Relay Brick launches out of the Deployer.

The microcontroller also provides the user with status information by communicating successes or failures of its actions to the CANR, which relays them back to the control station. As with the Relay Bricks, a user interface window provides shut down and available battery capacity readout features.

3.4 Status

The goal of this project is to develop and deliver four separate systems for four UGV platforms: the PackBot EOD, TAGS, Wolverine, and URBOT. The PackBot payload area, being the smallest of all, sets the size constraint of the Deployer and the Relay Bricks. In the current stage of development the Relay Brick prototype has been designed and is being fine tuned. The Deployer mechanical and electrical designs are underway. In addition, minor code adjustments to the network code are being made.

The end users of these systems will be the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), the Tanks Automotive Research, Development and Engineering Center (TARDEC), and SSC-San Diego. One system will be delivered to NAVEODTECHDIV for use on the PackBot EOD robot, which is part of the Man Transportable Robotic Systems (MTRS) program. Two systems will be delivered to TARDEC for use on the Tactical Amphibious Ground Support (TAGS) and Wolverine platforms. The fourth system is for in-house research, to be used on the Urban Robot (URBOT).

4. Conclusion

High frequency, wireless digital communications used by tactical robots operating in urban environments require a LOS to be maintained with the control station, which may be impossible to achieve. The proposed solution to this problem is to use a radio relaying system. The proposed system includes several relay radios, known as Relay Bricks that are carried in a Deployer module, which in turn is carried by the mobile robot as a payload. By monitoring the network, the Deployer will release a Relay Brick before the link between the control station and the robot is broken, in order to maintain the communications link. This occurs transparently and without dependence on the user. The system is designed for ease of use and minimal effort on the part of the user for initial setup and final collection and reuse of the Relay Bricks.

Future work will consist of minimizing the size of the system by developing smaller relay radios that consume less power. In addition, improved wireless protocols will be used that offer greater data rates and improved security. The availability of analog-to-digital converters and various communications bus interfaces allows simple addition of various sensors to the Relay Bricks, turning the Relay Bricks into stand-alone networked sensors that can provide rear-guard functions to the robot.

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